ONTOLOGICAL MODELLING FOR CONSEQUENCE-DRIVEN LEARNING: A HUMAN-CENTRED SIMULATION APPROACH TO SMART PROSTHESIS DESIGN AND EDUCATION

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ABSTRACT
The increasing demand for personalised, adaptive prosthetic solutions required to cater for evolving amputee needs emphasises the importance of intelligent, human-centred Product-Service Systems (PSS) that support amputees throughout their prosthesis life cycle. This paper presents adProLiSS (Adaptive Prosthesis Life-Cycle Service System), a novel framework designed to enhance prosthesis design, development, and aftercare by integrating ontological modelling, supported by adaptive AI for data-driven decision-making with real-time stakeholder collaboration, catering for evolving amputee needs. adProLiSS enables prosthetists, physiotherapists, and other healthcare professionals to explore 'what if' scenarios, serving as both a decision-support and educational tool for complex prosthesis design and aftercare challenges. By capturing the consequences of prosthesis interactions across life-cycle stakeholders (e.g. amputees, prosthetists, physios, service technicians), the system provides valuable insights to inform design and re-design decisions. Embedded sensors collect real-time data on key parameters such as socket pressure, temperature, gait speed, and step count, allowing for proactive management of issues like discomfort and ulcer risk. This data is processed through a digital twin model, enabling stakeholders to simulate and respond to real-world scenarios, such as patient falls or emerging health concerns.

The framework fosters experiential, hands-on learning, equipping healthcare practitioners and prosthesis designers with practical skills in decision-making and consequence analysis. By bridging theoretical knowledge with applied practice, it enhances cross-disciplinary collaboration in smart prosthesis management.

Initial evaluations demonstrate the potential of adProLiSS in improving prosthesis design, aftercare, and stakeholder education. Its simulation-based approach supports targeted training, ensuring practitioners are better prepared for the dynamic, evolving needs of amputees in the era of data-driven, adaptive healthcare systems.

Keywords: Human-centred design, product service systems, participatory design, consequence driven learning

1 INTRODUCTION
The increasing demand for individualised and adaptive prosthetic solutions highlights the need for intelligent, human-centred Product-Service Systems (PSS) that support amputees and their evolving needs throughout their prosthesis life cycle. Traditional prosthesis design, development and aftercare approaches [1] involve multiple stakeholders, such as amputees, prosthetists, standard parts designers and manufacturers, and healthcare professionals. However, limited interaction occurs between these stakeholders, resulting in the lack of 'knowledge of amputee consequences' encountered by amputees and their prosthesis during the design and development processes [2]. This demonstrates an inability to integrate real-time data, user feedback, and adaptive learning into the decision-making process [2]. Additionally, current amputee healthcare systems lack structured approaches for prosthesis life-cycle management that effectively capture and exploit 'knowledge of amputee consequences'. The traditional reliance on subjective feedback and disparate data sources complicates the decision-making process, leading to challenges in addressing individual amputee needs and preferences effectively. Consequently,

evolving amputee needs are insufficiently addressed during prosthesis design and development processes.
To tackle these issues, this research introduces the adProLiSS framework [3–5] that enhances stakeholder collaboration [6–9], enables sharing of ‘knowledge of amputee consequences’ [10] to support on-going prosthesis management and evolving amputee aftercare service needs. This builds upon our earlier work on the Ontology-Driven Consequence Mapping Model [11], which laid the foundation for modelling cause-and-effect relationships between prosthesis decisions and their impact on amputees. While that model focused on visualising consequence chains, adProLiSS extends this into a dynamic, real-time simulation framework.
Our framework builds upon human-centred PSS [12, 13] principles and ontology-driven modelling [14–17], it embeds an ontological representation of prosthesis system design, development, and aftercare. This approach facilitates real-time stakeholder decision-making, predictive maintenance, and improved prosthesis quality, personalisation, and long-term usability. Additionally, by integrating an amputee consequence-driven decision support model, the adProLiSS framework enables prosthesis designers to visualise the impact of their decisions using real-time data from smart prosthetics and stakeholder experiences. The adProLiSS framework also serves as an educational environment that promotes cross-disciplinary learning among stakeholders, ultimately aiming to improve the overall prosthesis experience for amputees.

2 HUMAN-CENTRED PRODUCT-SERVICE SYSTEMS FOR SMART PROSTHESIS DESIGN

Developing an effective human-centred PSS for smart prosthesis design requires a structured approach that integrates knowledge representation, iterative stakeholder engagement, real-time data utilisation, and consequence-driven learning. The following subsections examine these key elements, illustrating how adProLiSS facilitates adaptive prosthesis management and informed decision-making across the prosthesis life cycle.

2.1 Ontology-Driven Human-Centred Design for Prosthesis Development

Human-centred design (HCD) is a problem-solving approach prioritising user needs, expectations, behaviours and relationships of users [18, 19]. In prosthesis development, this means shifting from a standardised, one-size-fits-all approach to an adaptive, consequence-driven model that evolves with amputee requirements. However, translating user experiences into structured, reusable knowledge that informs prosthesis design decisions remains a challenge.
Ontology-based knowledge representation addresses this by formally capturing ‘knowledge of amputee consequences’, the real-world experiences, challenges, and adaptation needs encountered by amputees and their prostheses. By embedding this knowledge into a shared ontological model, HCD transitions from subjective feedback to structured decision-making, enabling: standardised yet flexible decision-making across different prosthesis design and aftercare processes; real-time consequence analysis by linking patient-specific data with structured medical, biomechanical and design knowledge; and cross-disciplinary collaboration through a shared, machine-readable knowledge framework that connects prosthetists, designers, amputees and healthcare professionals.
Within adProLiSS, ontology refers to a structured, hierarchical representation of knowledge capturing entities, relationships, and consequences relevant to the prosthesis life cycle. At the design stage, it serves as a foundation for integrating stakeholder knowledge and informing decisions through predictive modelling. At the analysis stage, the ontology supports post-decision evaluation by mapping real-world outcomes back to initial design choices, facilitating learning and continuous improvement through consequence-driven feedback loops.
In addition, adaptive AI supports the ontology-driven model by identifying patterns in real-time prosthesis data, such as gait irregularities, pressure points, or sudden activity changes, and suggesting recommendations accordingly. For instance, fall detection and ulcer prediction mechanisms are enhanced through machine learning techniques trained on historical and sensor data. This adaptive layer ensures the system not only provides static decision support but evolves with the patient, aligning with the framework’s goal of dynamic, personalised care.

This ontology-driven approach transforms implicit and explicit stakeholder knowledge into a computationally accessible and continually updated framework, ensuring that amputee needs, design choices, and long-term prosthesis management are informed by structured, evolving data.

2.2 Iterative Stakeholder Engagement for User-Driven Prosthesis Development

A key aspect of adProLiSS is its ability to continuously collect and integrate data from multiple stakeholders, including amputees, prosthetists, physiotherapists, and service technicians. Each stakeholder group engages with prosthetic devices at different life-cycle stages, prioritising different concerns: Amputees seek comfort, functionality, and seamless integration into daily life; Prosthetists and designers require tools to optimise fit, reduce failure rates, and personalise prosthesis development; Physiotherapists focus on rehabilitation, gait correction, and movement efficiency; and Service technicians need to anticipate maintenance and repair requirements. By embedding stakeholder feedback into the ontology-driven consequence model, adProLiSS ensures that design and decision-making are informed by real-world experiences rather than theoretical assumptions.

2.3 Real-Time Data Integration for Adaptive Prosthesis Management

A core element of human-centred smart prosthesis design is the ability to dynamically adjust to evolving user needs. The adProLiSS framework plays a critical role here by structuring real-time sensor data from smart prosthetics in a way that allows for automated reasoning, pattern recognition, and predictive maintenance. adProLiSS leverages this approach to track key parameters, such as: Socket pressure to prevent discomfort and ulceration; Gait speed and step count to assess mobility patterns; Pressure, temperature and humidity variations indicating potential infections or skin irritation; Activity levels and weight distribution affecting overall prosthesis performance.

adProLiSS enables context-aware interpretation, allowing prostheses to adapt based on both sensor feedback and patient-specific health and lifestyle data.

2.4 Digital-Twins for Stakeholder Learning and Decision Support

Human-centred design extends beyond physical prostheses to stakeholder education and training. adProLiSS incorporates an ontology-supported digital twin model, a virtual simulation of the prosthesis system that allows stakeholders to explore and visualise ‘what-if’ scenarios before making design decisions (such as selecting the right knee and ankle sub-systems to suit the amputee’s required mobility). By utilising ontology-driven simulations, stakeholders can: Prosthesis designers can visualise the impact of material choices, socket designs, knee or ankle sub-systems, and structural configurations before physical production; Healthcare practitioners can simulate responses to fall detection alerts and pressure-induced ulcer risks, preparing them for real-world situations; Amputees can interact with the system to gain a better understanding of their prosthesis’ functionality and maintenance requirements.

Additionally, by embedding structured consequence knowledge into this interactive simulation, novice prosthesis designers receive progressive, hands-on training, reinforcing experiential learning and bridging the gap between theoretical design knowledge and real-world prosthesis use.

2.5 Cross-Disciplinary Collaboration in Prosthesis Design and Aftercare

Prosthesis development involves multiple disciplines, engineering, healthcare, rehabilitation, and data science, each bringing unique expertise but often working in silos. adProLiSS facilitates integrated communication across disciplines by: Structuring prosthesis life-cycle data in a shared ontology to ensure consistent terminology and understanding; Using AI-driven decision support to bridge the knowledge gap between engineering design and medical application; Encouraging stakeholders to engage in collaborative design iterations, ensuring that all voices are considered in the prosthesis development process. This ontology-based, human-centred PSS approach ensures that design, manufacturing, and aftercare services remain adaptive, inclusive, and effective.

3 IMPLEMENTATION OF A CONSEQUENCE-DRIVEN LEARNING APPROACH IN PROSTHESIS DESIGN

This paper extends our work [11] on the Ontology-Driven Consequence Mapping Model (Figure 1), which enhances prosthesis design decision-making by integrating real-time patient-prosthesis data and extends its application to a learning-driven context. The previous work focused on integrating real-time patient-prosthesis data with the consequences of design choices, forming experiential knowledge to support stakeholder collaboration and optimise design choices. In contrast, this paper explores how the same ontology-driven approach can be leveraged for consequence-driven learning, enabling stakeholders to simulate and analyse the impact of their design decisions before implementation. By embedding this model into a human-centred simulation, this research improves stakeholder understanding of prosthesis design trade-offs. Its foster more informed decision-making and enhances cross-disciplinary learning in prosthetic development and aftercare.

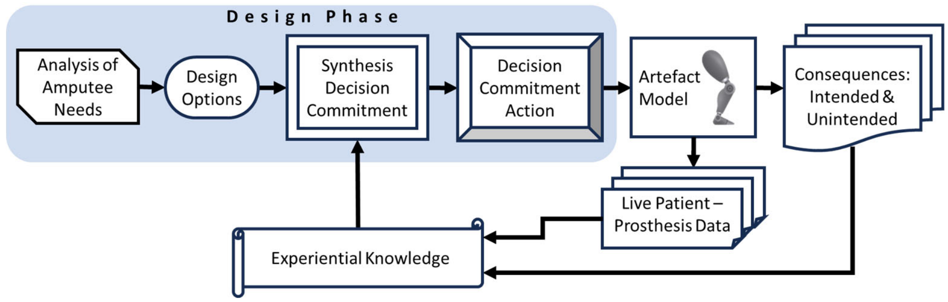

Figure 1. The Ontology-Driven Consequence Mapping Model

3.1 adProLiSS Learning and Consequence Simulator

The adProLiSS Learning & Consequence Simulator (adProLiSS-LCS) (Figure 2) is an interactive tool designed to enable users to visualise and simulate the process of prosthesis design and development. During the design phase, key stakeholders, including amputees and prosthetists, engage in discussions to assess the amputee's needs and define the desired outcomes of the prosthesis. Within the adProLiSS-LCS environment, users can access a comprehensive database of prosthesis sub-systems (e.g., knee or ankle sub-systems). By selecting a sub-system icon, its functional attributes and compatibility information are displayed, facilitating informed design choices.

Once users are familiar with the available options, they can configure the prosthesis by selecting the required sub-system components from a drop-down menu. As each selection is made, the system dynamically presents functional insights and recommended pairings, guiding users towards optimal design decisions.

Upon finalising the prosthesis configuration, the simulator generates predicted outcomes, leveraging experiential knowledge derived from iterative patient-prosthesis data and knowledge of amputee consequences gained through different patient-prosthesis meetings [20] with key stakeholders concerned with amputee and prosthesis aftercare. These outcomes provide an assessment of suitability, indicating whether the selected configuration meets the amputee's needs accurately or if potential mismatches may lead to functional failures.

For smart prosthesis configurations, adProLiSS-LCS offers an adaptive menu with additional features, such as embedded sensors for monitoring socket ulcer formation or tracking amputee mobility. After finalising their selections, users receive predictive insights into the prosthesis' expected performance, enabling data-driven decisions that enhance the adaptability and effectiveness of the prosthesis.

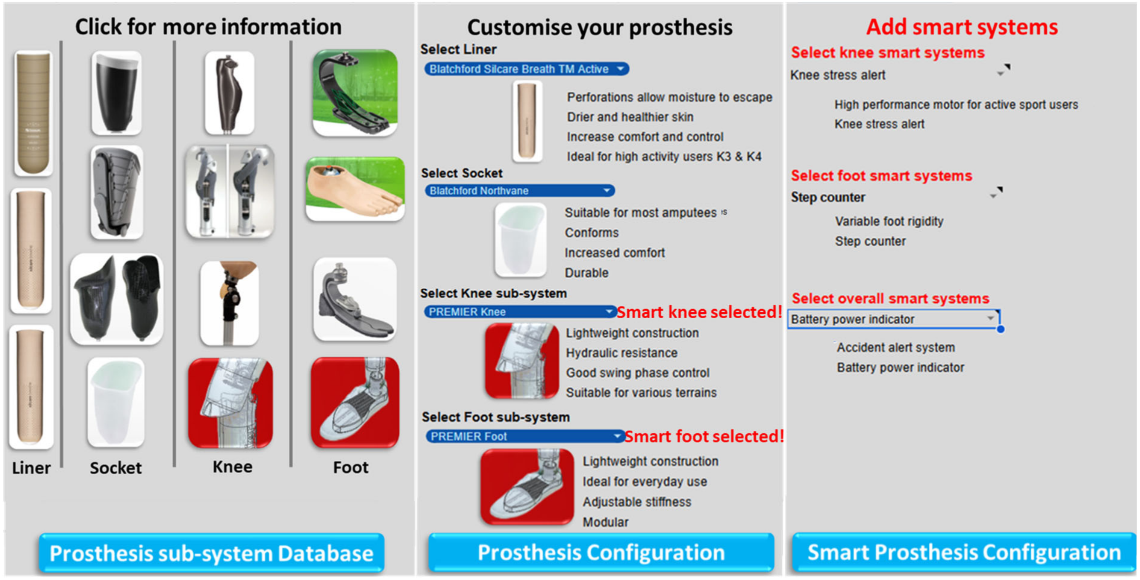

Figure 2. adProLiSS Learning and Consequence Simulator (adProLiSS-LCS)

4 DISCUSSION AND CONCLUSION

The initial evaluations of the adProLiSS-LCS have been met with positive feedback, highlighting its effectiveness as a hands-on, experiential learning tool. By enabling stakeholders to simulate and test prosthesis configurations in real-time, the system facilitates iterative refinements based on real-world data and simulated consequences. This interactive approach enhances collaborative decision-making, fostering a deeper understanding of prosthesis design trade-offs and their impact on user experience.

Future research will focus on further refining adProLiSS-LCS, with particular emphasis on enhancing predictive accuracy and optimising real-time learning pathways. Advancements in its adaptive AI models will enable continuous refinement of prosthesis recommendations, informed by evolving user feedback, knowledge of amputee consequences and health data. Additionally, efforts will be directed towards improving the system's user interface to ensure an intuitive and accessible experience for all stakeholders.

Further evaluations will also assess the scalability of adProLiSS-LCS and its integration into both clinical and design practices. As adoption increases, the system's effectiveness is expected to improve, driven by a growing repository of stakeholder insights and data-driven refinements. Ultimately, adProLiSS-LCS has the potential to transform prosthesis design and aftercare by fostering a more informed, collaborative, and adaptive development process.

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